Production of two Higgses at the Large Hadron Collider in CP-violating MSSM

Priyotosh Bandyopadhyay
University of Helsinki & Helsinki Institute of Physics

August 29, 2013
SUSY 13

in collaboration with Katri Huitu

arXiv:1106.5108v2 [hep-ph]

Outline

Sources of CP violating phases in MSSM

- In SM we have two CP-violating phases, $\theta_{\rm QCD}$ and $\delta_{\rm CKM}$.
- Unlike SM, MSSM is the source of many other CP-violating phases.
- In the MSSM, CP-violating phases appear in the μ term of the superpotential,

$$W \supset \mu H_u \cdot H_d$$

- and in the soft-SUSY breaking terms as follows:

$$
\begin{aligned}
-\mathcal{L}_{\rm soft} \supset\ & \\
& \frac{1}{2}(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \mathrm{h.c.}) \\
& + \widetilde{Q}^\dagger \mathbf{M}^2_{\widetilde{\mathbf{Q}}} \widetilde{Q} + \widetilde{L}^\dagger \mathbf{M}^2_{\widetilde{\mathbf{L}}} \widetilde{L} + \widetilde{u}^*_R \mathbf{M}^2_{\widetilde{\mathbf{u}}} \widetilde{u}_R + \widetilde{d}^*_R \mathbf{M}^2_{\widetilde{\mathbf{d}}} \widetilde{d}_R + \widetilde{e}^*_R \mathbf{M}^2_{\widetilde{\mathbf{e}}} \widetilde{e}_R \\
& - m_1^2 H_d^* H_d - m_2^2 H_u^* H_u - (m_{12}^2 H_u H_d + \mathrm{h.c.}) \\
& + (\widetilde{u}^*_R \mathbf{A_u} \widetilde{Q} H_u - \widetilde{d}^*_R \mathbf{A_d} \widetilde{Q} H_d - \widetilde{e}^*_R \mathbf{A_e} \widetilde{L} H_d + \mathrm{h.c.})
\end{aligned}
$$

CP violation in MSSM contd.

- CP violation in the Higgs potential of the MSSM leads to mixing terms between the CP-even and CP-odd Higgs fields at loop-level. Pilaftsis, et al.
- In the weak basis (G^0, a, ϕ_1, ϕ_2), the neutral Higgs-boson mass matrix $\mathcal{M}_0^2$ may be cast into the form

$$\mathcal{M}_0^2 = \begin{pmatrix} \widehat{\mathcal{M}}_P^2 & \mathcal{M}_{PS}^2 \\ \mathcal{M}_{SP}^2 & \mathcal{M}_S^2 \end{pmatrix}$$

where,

$$\widehat{\mathcal{M}}_P^2 \Rightarrow \begin{pmatrix} G^0 \\ a \end{pmatrix} \leftrightarrow \begin{pmatrix} G^0 \\ a \end{pmatrix} \qquad \mathcal{M}_S^2 \Rightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \leftrightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\mathcal{M}_{PS}^2 = (\mathcal{M}_{SP}^2)^T \qquad \Rightarrow \begin{pmatrix} G^0 \\ a \end{pmatrix} \leftrightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

CP violation in MSSM contd.

- The mixing term :

$$\mathcal{M}^2_{SP} = -\frac{T_a}{v}\begin{pmatrix} s_\beta & c_\beta \\ -c_\beta & s_\beta \end{pmatrix} \simeq \mathcal{O}\left(\frac{m_t^4}{v^2}\frac{|\mu||A_t|}{32\pi^2 M^2_{\mathrm{SUSY}}}\right)\sin\phi_{\mathrm{CP}}$$

  where,

  $\phi_{\mathrm{CP}} = \arg(A_t\mu) + \xi \quad M^2_{\mathrm{SUSY}} = \frac{1}{2}\left(m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}\right)$

- CP-phases of gaugino mass parameter also contribute through the threshold corrections $\sim f(M^*\mu^*)$.
- Not all are independent, physical ovservables depend on some combinations.

CP violation in MSSM contd.

- G_0 is massless: Doesn't mix with other neutral fields.
- $\mathcal{M}_0^2$ reduces to a (3×3)-dimensional matrix, $\mathcal{M}_N^2$ in the basis (a, ϕ_1, ϕ_2).
- $\mathcal{M}_N^2$ is symmetric, we can diagonalize it by means of an orthogonal rotation O as follows:

$$O^T \mathcal{M}_N^2 O = \mathrm{diag}\,(M_{h_3}^2,\ M_{h_2}^2,\ M_{h_1}^2)\ .$$

- Where,

$$M_{h_1} \leq M_{h_2} \leq M_{h_3}\ .$$

- Do not have any definite CP properties.

The CPX scenario

- The mixing become significant when $\mathrm{Im}(\mu A_t/M^2_{SUSY})$ is large.
- Motivated by this following CP-violating benchmark scenario CPX was introduced in the literature.
  Carena,Pilaftsis, Ellis, Wagner

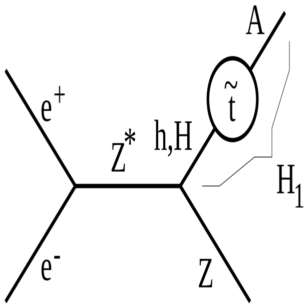
$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY}\,,$$
$$|\mu| = 4\,M_{\rm SUSY}\,,\quad |A_{t,b,\tau}| = 2\,M_{\rm SUSY}\,,\quad |M_3| = 1\ \ {\rm TeV}.$$

- The parameter $\tan\beta$, $M_{H^\pm}$, and $M_{\rm SUSY}$ can be varied.
- For CP phases, $\Phi_A = \Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau}$, we have two physical phases to vary: Φ_A and $\Phi_3 = {\rm Arg}(M_3)$.
- Special case:

$$M_{SUSY} = 500 \text{ GeV}, \quad \Phi_A = \Phi_{M_3} = 90^\circ$$
$$M_2 = 2M_1 = 200 \text{ GeV}, \quad \tan\beta = 5 - 10$$

Outline

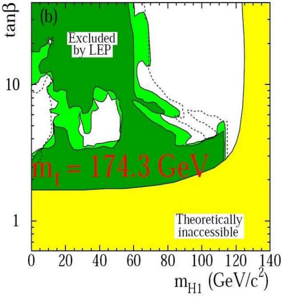
The Experimental constraints



- $h_1 \sim$ CP-odd.
- As $h_1 \simeq A \Rightarrow Z - Z - h_1$ coupling goes down.
  $\Rightarrow$ could not probe the channel in the CPX scenario at LEP.

The Experimental constraints

- LEP put a lower bound on SM Higgs: $m_H \geq 114.4$ GeV.
- The 'LEP hole' in CPX scenario



- Finally both CMS and ATLAS at LHC found a Higgs like particle around 125 GeV.

The Experimental constraints

- With $\sim$ 125 GeV Higgs discovery at the LHC in July, 2012, we should have one Higgs boson around $\sim$ 125 GeV.
- This severely constrains the scenario of buried Higgs, i.e., light Higgs(es) below 100 GeV.
- There are also many indirect experimental bounds that put the scenario in the challenging situation.
- We need to deviate from so called 'CPX' scenario, to evade some of the experimental bounds.

The Experimental constraints

- The CP-violating phases are mostly constrained by the EDM bounds of different atoms.
- EDM of Thallium with 2σ upper bound is $|d_{Tl}| < 1.3 \times 10^{-24}$ e cm.
- This constrains the relative angles between M_1 and M_2 also ϕ_{A_t}, ϕ_{M_3}.
- Though it is possible to get region where the one loop-SUSY contribution and light Higgs mediated two-loop contribution are comparable and tend to cancel each other.
  Cheung et al.
- Very light Higgs $m_{h_1} \lesssim 8$ GeV is ruled out from bottomonium decay $\Upsilon(1S) \to \gamma h_1$ P. Franzini et al.

The constraints from B-observables

- $\text{Br}(B_s \to \mu\mu)$, which recently has come down by two orders of magnitude can severely constrain this scenario.
  The 2σ bound from CMS is $\sim 1.4 - 6 \times 10^{-9}$.
- $\text{Br}(B_s \to \mu\mu)$ grows high as $\tan\beta$ grows.
- For the cancellation we use GIM operative point mechanism.
- So we vary $\rho = \frac{Q_{1,2}}{Q_3}$ the ratio of first two generation of the squark masses over the third generation squark masses. We see the cancellation happens when $\rho \sim 0.8 - 1.9$.

The constraints from B-observables

- This predicts very light first two generation masses for some cases.
- To evade such light mass bound coming from $jets + \not{p}_T$ at the LHC, we have to take large LSP masses which would make the jets rather soft.
- Unlike $B_s \to \mu\mu$ case $\mathrm{Br}(B_s \to X_s\gamma)$ decreases as $\tan\beta$ increases. This is because the charged Higgs contribution is suppressed due to the threshold corrections at higher $\tan\beta$. Carena et al., Degrassi et al.

Other bound from LHC

- We also included recent bounds on third-generation squark masses and LSP from 8 TeV LHC.
- We also choose $m_3 = 1.4$ TeV to satisfy recent gluino mass bound.
- For this choice of gluino mass we find it is very difficult to get $m_{h_3} \gtrsim 124$ GeV by using CPsuperH [1]

[1] There is $\sim 2 - 3$ GeV uncertainty in Higgs mass calculated by CPsuperH and FeynHiggs

Outline

Benchmark points

- For this paper we have used CPsuperH2.0 for the mass spectrum and the other observables. We varied $\tan\beta$ and $m_{H^\pm}$ as usual as we move to different points in the 'LEP hole'.
- Top mass was taken 173.2 GeV.

Mass	BP1 in GeV	BP2 in GeV	BP3 in GeV
m_{h_1}	54.25	25.00	123.50
m_{h_2}	95.00	94.70	490.70
m_{h_3}	124.40	124.60	494.70

Outline

Cross-sections

BPs	Cross-section in fb					
	$\sigma_{h_1 h_2}$	$\sigma_{h_1 h_3}$	$\sigma_{h_1 h_1}$	$\sigma_{h_2 h_2}$	$\sigma_{h_3 h_3}$	$\sigma_{h_2 h_3}$
BP1	908.02	47.02	5393.50	24.11	7.83	6.92
BP2	1858.89	45.23	33086.7	20.35	5.19	3.91
BP3	1.73×10^{-2}	1.0×10^{-2}	18.6	8.6×10^{-3}	5.7×10^{-3}	0.47

Table: Cross-sections (in fb) of two Higgs productions ($h_{2,3} h_i = 1, 2, 3$) at the LHC with $E_{cm} = 14$ TeV for the benchmark points.

$\star$ $h_i Z$ processes also contribute in final states.

Higgs decays

- The buried Higgs bosons h_1, h_2 mainly decay to $b\bar{b}$ and $\tau\bar{\tau}$.
- h_3 when around 125 GeV, can decay to h_1 pair.
- The heavier Higgs bosons, h_2, h_3 can have off-shell or on-shell decay to $h_1 Z$ depending on benchmark points.
- We investigate the final states with b, τ-jets and leptons.

Set up for the numerical session

- Event generation: `CalcHEP` interfaced with`CPsuperH`.
- (Generated events + Relevant CPV-Brs) $\Rightarrow$ passed to PYTHIA(via SLHA).
- ISR/FSR, hadronization and jet formation: from PYTHIA.
- We use Fastjet-3.0.3 for the jet formation
- the calorimeter coverage is $|\eta| < 4.5$
- $p_{T,min}^{jet} = 20$ GeV and jets are ordered in p_T
- leptons ($\ell = \mathrm{e},\ \mu$) are selected with $p_T \geq 20$ GeV and $|\eta| \leq 2.5$
- no jet should match with a hard lepton in the event
- $\Delta R_{lj} \geq 0.4$ and $\Delta R_{ll} \geq 0.2$
- hadronic activity within a cone of $\Delta R = 0.3$ between two isolated leptons should be $\leq 0.5 p_T^{\ell}$ GeV in the specified cone.

Kinematic distributions

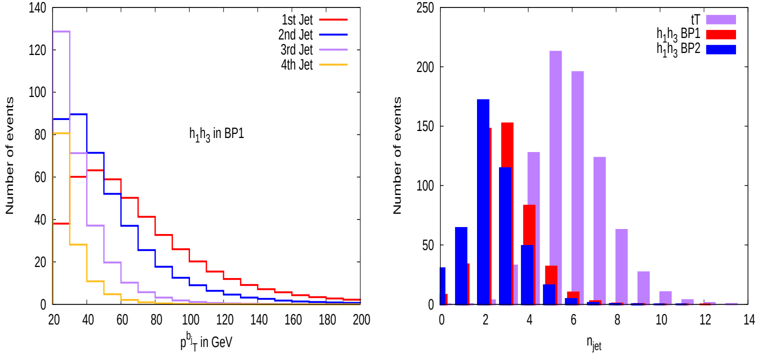


Figure: $p_T^{b_{jet}}$ distribution for $h_1 h_3$ for BP1 and Jet multiplicity distributions for $h_1 h_3$ for BP1, BP2 and $t\bar{t}$ at an integrated luminosity of $\mathcal{L} = 10\ \text{fb}^{-1}$.

$b\bar{b}$ invariant mass distributions

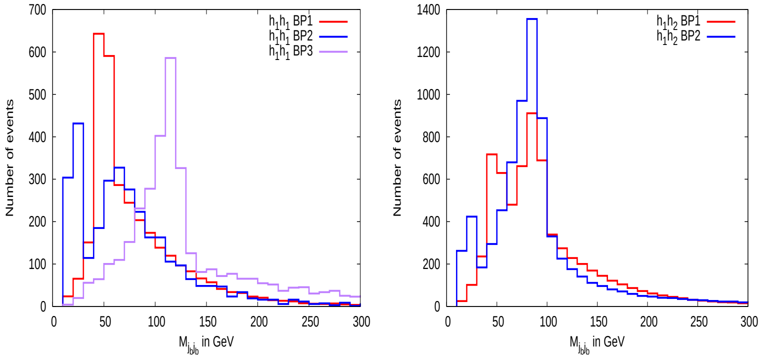
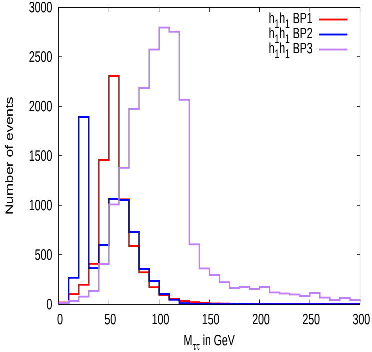


Figure: b-jet invariant mass distribution coming (a) from $h_1 h_1$, (b) from $h_1 h_2$ for benchmark pints at an integrated luminosity of $\mathcal{L} = 10$ fb^{-1}.

$\tau\bar{\tau}$ invariant mass distributions



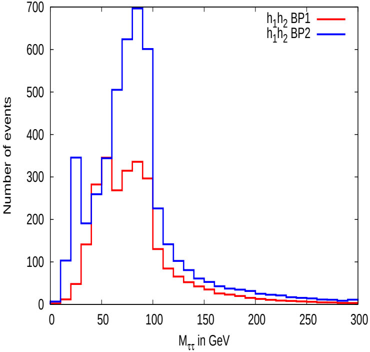


Figure: τ-jet invariant mass distribution coming (a) from h_1h_1, (b) from h_1h_2 for benchmark pints at an integrated luminosity of $\mathcal{L} = 10$ fb^{-1}.

$3b + 2\tau$ final states at the LHC

- $$\begin{aligned} pp &\rightarrow h_1 h_{2,3}, \\ &\rightarrow h_1\ Zh_1(h_1 h_1) \rightarrow 4b + 2\tau. \end{aligned}$$
- We investigate
  $\mathrm{sig1}: \mathrm{n_{jets}} \leq 5 + \geq 3\mathrm{b} - \mathrm{jet} + \geq 2\tau - \mathrm{jet} + \not{p}_\mathrm{T} \leq 30\,\mathrm{GeV}.$
- We consider $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}W$, ZZ and $t\bar{t}b\bar{b}$ as the main SM backgrounds.
- BP1 has 7.1σ significance over backgrounds at an integrated luminosity of 10 fb^{-1}.
- For BP2 and BP3 it is 4.5σ and 0.5σ, respectively.
- Higgs boson mass peaks can be extracted by putting window cuts around bb or $\tau\tau$ invariant mass mass at relatively higher luminosity.

$2b + 2\tau$ final states at the LHC

- Unlike for the other benchmark points, in BP3, $h_3 \to h_1 h_1$ is very small, and h_3 mostly decays to b or tau pairs.
- $2b + 2\tau$ looks promising and we choose $\mathrm{sig2:n_{jets}} \leq 5 + \geq 2\mathrm{b-jet} + \geq 2\tau - \mathrm{jet} + \not{p}_T \leq 30\,\mathrm{GeV}$.
- It has 13.5 σ, 10σ and 0.6σ significance at 10 fb^{-1} for BP1, BP2 and BP3, respectively.
- h_1 peak as $|m_{bb} - m_{h_1}| \leq 10$ GeV has significance of 12σ and 10.4σ for BP1 and BP2 at 10 fb $^{-1}$.
- Even h_2 mass peak has 5σ significance at 10 fb^{-1} for BP1 & BP2

$2b + 2\tau$ final states at the LHC

Signal	Benchmark Points			Backgrounds				
	BP1	BP2	BP3	$t\bar{t}$	$t\bar{t}Z$	$t\bar{t}W$	ZZ	$t\bar{t}b\bar{b}$
sig2	501.30	350.80	19.00	812.10	0.30	0.50	57.70	0.20
sig2+$\|m_{bb} - m_{h_1}\| \leq 10$ GeV	195.00	129.00	4.00	65.00 23.70 59.00	0.04 0.00 0.05	0.05 0.00 0.05	6.20 0.60 0.60	0.00 0.00 0.00
sig2+$\|m_{bb} - m_{h_2}\| \leq 10$ GeV	69.00	56.00	0.00	103.00 104.10 1.0	0.01 0.01 0.00	0.08 0.08 0.00	15.00 16.00 0.00	0.06 0.06 0.00
sig2+$\|m_{bb} - m_{h_3}\| \leq 10$ GeV	22.00	8.20	0.00	60.00 60.00 1.00	0.04 0.04 0.00	0.06 0.06 0.00	0.30 0.30 0.00	0.00 0.00 0.00
sig2+$\|m_{\tau\tau} - m_{h1}\| \leq 10$ GeV	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sig2+$\|m_{\tau\tau} - m_{h2}\| \leq 10$ GeV	52.00	33.00	0.20	101.00 103.00 1.00	0.04 0.04 0.00	0.10 0.10 0.00	17.00 17.00 0.00	0.06 0.06 0.00
sig2+$\|m_{\tau\tau} - m_{h3}\| \leq 10$ GeV	4.00	3.00	0.10	105.00 104.00 1.00	0.01 0.03 0.00	0.07 0.07 0.00	0.30 0.20 0.00	0.06 0.00 0.00

Table: Number of signal events for the benchmark points and backgrounds at an integrated luminosity of 10 fb^{-1} at the LHC with $E_{cm} = 14$ TeV.

2ℓ final states at the LHC

- Higgs bosons decay to lepton pair branching fraction is small.
- Final states with dilepton can be crucial for precision measurement in of invariant mass peak.
- We study, final states with 2μ or $2e$.
- The signal significance is 5σ and 3σ for BP2 and BP1, respectively at 10 fb^{-1}.
- h_1 mass peak gets a significance of 7.6σ for BP2 at 10 fb^{-1} of luminosity and for other benchmark points one needs higher luminosity.

Outline

Conclusion and remarks

- Higgs pair production is interesting in spite of being electroweak production process.
- Specially $2b + 2\tau$ (Sig2) final state looks promising.
- It is possible to reconstruct the Higgs mass peak, both via bb invariant mass and through $\tau\tau$ invariant mass distribution.
- leptonic final state can come handy for light (buried) Higgs search.
- LHC at 14 TeV has a great chance to explore these scenarios
- In particular for some benchmark points the hint could come earlier.

Thank you

Outline

CPX:"LEP-hole" and Earlier works

- Sum rule:

$$g^2_{h_i VV} + \mid g_{h_i H^- W^+} \mid^2 = 1$$

$$g^2_{h_i VV} \downarrow \quad \Rightarrow \quad g_{h_i H^- W^+} \uparrow$$

- New channel: $pp \to H^+ h_1 \to h_1 h_1 W^+ \to b\bar{b}b\bar{b}l\nu$
  Moretti, Gosh,
- New channel: $pp \to t\bar{t} + X \to bbbbqql\nu$
  Gosh, Roy and Godbole
- As $g_{\tilde{t}_1 \tilde{t}_1^* h_1} \uparrow$ and $g_{\tilde{t}_1 \tilde{t}_1^* h_3} \downarrow$
  Low m_{h_1}($\leq$60 GeV)
  $\Rightarrow \tilde{t}_1 \tilde{t}_1^* h_1 \to 4b + OSD + \not{p}_T$ can be promising
  Bandyopadhyay, Datta, Datta, Mukhopadhyay
- Higgs production in third generation SUSY cascade, exploring $H^\pm \to h_1 W^\pm$ decay.

  P. Bandyopadhyay